Experimental Investigation of the Effects of Molten Particle Dynamics and Substrate Temperature on the Oxidation Resistance of Plasma-Sprayed $MoSi_2$ Coatings

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1. Introduction

Accident-tolerant fuels (ATF) and high-temperature structural materials used in next-generation nuclear systems must withstand extreme thermal loads and severe oxidizing environments[1]. In particular, Generation IV reactors operate under more harsh and demanding conditions than current systems, making high-temperature oxidation–induced degradation a critical reliability concern. High-temperature oxidation of structural alloys such as stainless steels, Inconel, and niobium-based alloys leads to strength degradation and thermal instability, ultimately compromising structural integrity and service lifetime.

$MoSi_2$ is a representative oxidation-resistant material that forms a dense and stable SiO_2 protective layer at elevated temperatures, exhibiting excellent resistance between 1000 and 1600°C [2]. Consequently, $MoSi_2$ coatings deposited via vacuum plasma spray(VPS) have gained significant attention as a promising surface coating solution to effectively prevent high-temperature oxidation.

This study aims to elucidate the influence of key physical parameters in the plasma spraying process on coating microstructure and oxidation resistance. Inspired by spray cooling studies, where the droplet Weber number (We) and substrate surface temperature govern droplet dynamics and heat transfer behavior, we hypothesize that the in-flight particle Weber number and substrate surface temperature (T_s) in plasma spraying play critical roles in determining splat morphology, stacking behavior, and the resulting coating properties[3].

To validate this hypothesis, $MoSi_2$ coatings were fabricated, and the in-flight particle Weber number (We), particle temperature (T_p), and substrate surface temperature (T_s) were systematically monitored and analyzed to quantitatively evaluate their influence on coating characteristics.

2. Experimental Methods and Results

$MoSi_2$ powders with an average particle size of 30 µm were deposited using a Vacuum Plasma Spray(**VPS**) system(Oerlikon Metco). By adjusting the plasma parameters, the in-flight particle temperature and velocity were controlled within the ranges of 2003–2504°C and 248–327 m/s, respectively. Stainless steel, Inconel 909, and Nb alloy substrates were employed. The substrate surface temperature was preheated to 250–360°C prior to deposition, and increased by approximately 400°C during the coating process.

To quantify the dynamic behavior of molten particles, the Weber number (We) was calculated as:

$$We = \frac{\rho U_m^2 D_m}{\sigma} \quad (1)$$

where ρ is the density of molten $MoSi_2$, U_m is the experimentally measured particle velocity, D_m is the particle diameter, and σ is the surface tension of the molten particle. The calculated Weber numbers ranged from approximately 6.4×10^3 to 1.12×10^4, indicating that inertial forces overwhelmingly dominated over surface tension under all coating conditions.

To investigate the correlation between particle dynamics and substrate thermal conditions, the relationship between the Weber number and substrate surface temperature for each coating condition is presented in Fig. 1. The figure illustrates coating formation after 3 spray cycles, with color indicating the presence or absence of a continuous coating layer.

Although all conditions corresponded to high Weber numbers, coating formation behavior varied depending on both Weber number and substrate temperature. For example, under the highest Weber number condition, a coating layer formed on the Inconel 909 substrate at a surface temperature of 250 °C. However, at a slightly

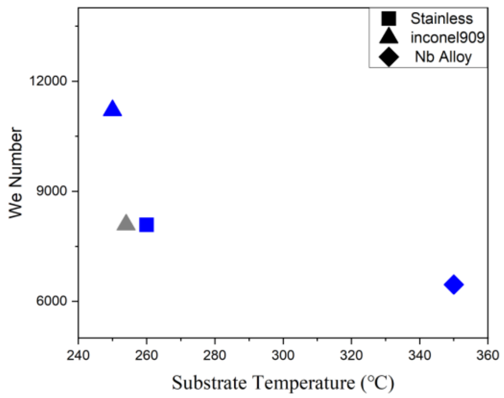

Fig. 1. Correlation between Weber number and substrate surface temperature

higher surface temperature of 254°C and a Weber number of approximately 8.0×10^3, no coating layer was formed. This demonstrates that even for the same substrate material, variations in Weber number can significantly influence coating formation.

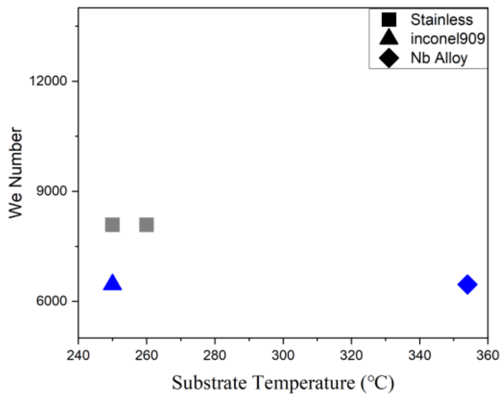

Fig. 2. Correlation between Weber number and substrate surface temperature after 5 spray cycles

The results for 5 spray cycles are shown in Fig. 2. For stainless steel substrates, no continuous coating layer was formed at surface temperatures of 250°C and 260°C, even under high Weber number conditions. In contrast, under relatively lower Weber number conditions, coating formation was observed on Inconel 909 and Nb alloy substrates.

These results suggest that increasing the number of spray cycles and consequently raising the substrate temperature during deposition is not sufficient to guarantee stable coating formation unless a critical surface temperature is reached. While the kinetic energy of the particles is an important factor governing coating formation, the substrate surface temperature plays a decisive role in achieving stable splat stacking and continuous coating growth. Even with increased deposition cycles, the substrate temperature may remain insufficient for stable coating layer formation.

3. Conclusions

Although all experimental conditions corresponded to a high Weber number regime, coating formation did not occur on the Inconel 909 substrate at 254°C or on the stainless steel substrates at 250°C and 260°C. These results indicate that while a high Weber number is a necessary condition for coating formation, it is not sufficient to ensure the development of a continuous coating layer.

Therefore, to achieve oxidation-resistant $MoSi_2$ coatings with reliable integrity, it is essential to secure not only sufficiently high particle temperature and Weber number but also a substrate surface temperature exceeding a critical threshold. The establishment of this critical thermal condition is indispensable for stable splat deposition and continuous coating growth.

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